PRECISION DETERMINATION OF THE TOP QUARK MASS

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For the CDF and DØ Collaborations

Abstract

The CDF and DØ collaborations have updated their measurements of the mass of the top quark using proton-antiproton collisions at $\sqrt{s}$=1.96 TeV produced at the Tevatron. The uncertainties in each of the of top-antitop decay channels have been reduced. The new Tevatron average for the mass of the top quark based on about $1\,\text{fb}^{-1}$ of data per experiment is $170.9\pm1.8\,\text{GeV}/c^2$.

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1 Introduction

The discovery of the top quark by the CDF and DØ collaborations 1995 [1] has marked the beginning of a successful physics program at the Tevatron. The mass of the top quark (M_t) is a fundamental parameter of the Standard Model (SM), but more importantly, its surprisingly high value gives the top quark particular relevance in the calculation of other SM parameters. Electroweak corrections to the W propagator introduce a quadratic dependence of the W boson mass (M_W) on M_t. M_W is also expected to depend logarithmically on the mass of the long-hypothesized but still unobserved Higgs boson (M_{H}). Thus, a precision measurement of M_t and M_W provides a mean to impose a constraint to M_{H}. The presence of further loop corrections in which heavy unknown particles are involved might lead to signatures beyond the SM. The Yukawa coupling to the Higgs field of $\mathcal{O}(1)$ indicates that the top quark might play a special role in the mechanism of electroweak symmetry breaking.

The determination of the top quark mass is therefore a very active topic in Tevatron Run-II. The top quark mass has been measured in all $t\bar{t}$ decay topologies with increasing precision. Improvements are based on the performance of the Tevatron, the better understanding of the detectors, and particularly on innovative analysis techniques. Here we report on the state-of-the-art of CDF and DØ measurements based on up to $1\,\mathrm{fb}^{-1}$ of analyzed data per experiment.

2 Experimental Challenges

The upgraded Tevatron complex started in 2001 to produce collisions of protons and antiprotons at $\sqrt{s} = 1.96\,\mathrm{TeV}$ with steadily increasing instantaneous luminosities up to a record of $3\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The CDF and DØ experiments [2] have integrated a luminosity of about $2\,\mathrm{fb}^{-1}$ each, the projected goal for the end of Run-II is 4-8 fb^{-1}. Both experiments are multipurpose detectors which cover the interaction points almost hermetically. The inner volumes contain precision tracking systems and silicon vertex detectors embedded in a solenoidal magnetic field. The magnets are surrounded by electromagnetic and hadronic calorimeters. The outermost parts consist of muon systems for the detection of penetrating particles. The experiments are running with a data taking efficiency of better than 80%.

At Tevatron energies, SM top quarks are mainly produced in pairs through quark-antiquark annihilation (85%) and gluon-gluon fusion (15%). The theoretical $t\bar{t}$-prodution cross section is 7.8±1.0 pb [3] for a top quark mass of $170\,\mathrm{GeV}/c^2$, which corresponds to approximately one top quark pair produced in 10^{10} inelastic collisions. The top quark does not hadronize and promptly undergoes the transition $t \rightarrow Wb$ with a branching ratio of BR~100%. The event signature is thus defined by the decay modes of the two W bosons. We

distinguish the "di-lepton" channel, $t\bar{t} \rightarrow (l_1^+ \nu_1 b)(l_2^- \bar{\nu_2}\bar{b})$ (5% fraction), the "lepton-jets" channel (30% fraction), $t\bar{t} \rightarrow (q_1\bar{q_2}b)(l^-\bar{\nu}\bar{b})$, and the "all-jets" channel, $t\bar{t} \rightarrow (q_1\bar{q_2}b)(q_3\bar{q_4}\bar{b})$ (44% fraction), where the q_i's stand for quarks and l denote an electron e or a muon μ (τ's are usually ignored).[1]

Top quark analyses require full detector capabilities. The measurement of the leptonic W decay modes relies on the clean identification of electrons and muons. The hermeticity of the calorimeter is essential for the partial reconstruction of the momentum of undetectable neutrinos through the measurement of the missing transverse energy. The reconstruction of the primary quarks from $t\bar{t}$ decays involves the accurate measurement of calorimeter energy deposits and their appropriate clustering into jets. Quark flavor information is provided by vertex detectors via the reconstruction of displaced vertices consistent with long-lived b-hadrons, which are present in all decay modes. The "b-tagging" is crucial to reduce background contributions and the number of possible jet-quark assignments.

Top quark measurements critically depend on the accurate knowledge of the jet energy scale (JES), which incorporates corrections of the raw jet energies for physics and instrumental effects as well as for jet definition artefacts. The JES is currently known *a priori* to a level of 2-3% for jets typical in $t\bar{t}$ events [4] and constitutes the dominant source of systematic uncertainties.

3 Measurement Techniques

The mass extraction techniques employed by CDF and DØ can be subdivided into two categories. The *Template Method* is based on the evaluation of one observable per event correlated with the top quark mass M_t, and a comparison of simulated distributions of this observable ("templates") with varying M_t with the data. Typically, some kind of reconstructed top quark mass m_t is taken, for example the output of the kinematic fit of a $t\bar{t}$ hypothesis to the event. Recent analyses have introduced the JES as a second template variable using distributions of the invariant di-jet mass m_W of the hadronically decaying W boson. The m_t and m_W distributions provide two-dimensional sample likelihoods which allow a simultaneous determination of M_t and the JES *in situ*. The Template Method is computationally simple, but it uses limited event information by evaluating just one or two numbers per event, and it treats well and badly reconstructed events equally. Refined Template Method analyses therefore apply weights to the events using further kinematic information.

The *Matrix Element Method* enhances the mass information by exploring the SM predictions for top quark dynamics. For each event, a probability density curve $\mathcal{P}(M_t)$ is extracted, which expresses the quality of the agreement

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[1] A review of top quark property measurements is given by M. Weber in these proceedings.

of the event with a signal or background process as a function of M_t. The per-event probabilities are multiplied, and the maximum position of the resulting curve gives the most likely value for M_t for the whole signal candidate sample. Recent measurements have extended the technique to allow the JES be re-adjusted *in situ* using the invariant mass of the W boson as a reference:

$$\mathcal{P}_{t\bar{t}}(x|M_t, \text{JES}) \propto \sum_{\text{comb}} \int \mathrm{d}\sigma_{t\bar{t}}(y|M_t)\mathrm{d}q_1\mathrm{d}q_2 f(q_1)f(q_2)w(x|y, \text{JES}) \ . \quad (1)$$

$\mathrm{d}\sigma_{t\bar{t}}$ denotes the differential $t\bar{t}$ cross-section (using a tree level matrix element) for a configuration of parton level momenta y, given M_t, and contains all integration details for the six-body phase space. $f(q_i)$ is the proton-parton density function for given momenta q_i of the two incoming quarks. The transfer functions $w(x|y, \text{JES})$ are probabilities of a set of variables x (*e.g.* transverse jet momenta) to be measured given a set of parton level quantities y (*e.g.* quark momenta) and a shift of the JES from its *a priori* known value. A JES hypothesis yielding to a W mass which is inconsistent with the known W mass and width penalizes the event probability. The transfer functions account for hadronization effects and detector resolution. The sum usually goes over all possible jet-quark permutations and neutrino solutions. The background probabilities are calculated analog to Eq. (1) but have no M_t dependence.

Since the method buys its increased statistical power by CPU-intensive numerical integrations, simplifying assumptions must be made in the interest of computational tractability. Lepton momenta and jet angles are often treated as exactly measured quantities, and only the probability density shapes of the dominant background types are calculated. Due to the various approximations, the method must be calibrated using the behavior of fully simulated Monte Carlo (MC) samples with known value for M_t.

Both methods depend on trustworthy physics event generators and detector simulations. The *in-situ* technique has the advantage that the largest part of the JES uncertainty becomes a statistical component of the top quark mass uncertainty, which thus will scale down as more luminosity is collected.

4 Measurements in the Lepton-Jets Channel

The lepton-jets channel is viewed as a good compromise between all decay modes because it has a reasonable branching fraction and a good S/B ratio between $\sim$0.2-10, dependent on the b-tag requirement. The final state is characterized by well defined kinematics with moderate combinatorial quark-jet ambiguity. There are twelve ways to assign jets to quarks if no b-tag information is used, and six (two) possibilities in case of one (two) b-tags (ignoring the physically equivalent permutations of the quarks from the W boson). The number of kinematic solutions doubles due to the twofold ambiguity of the neutrino longitudinal momentum.
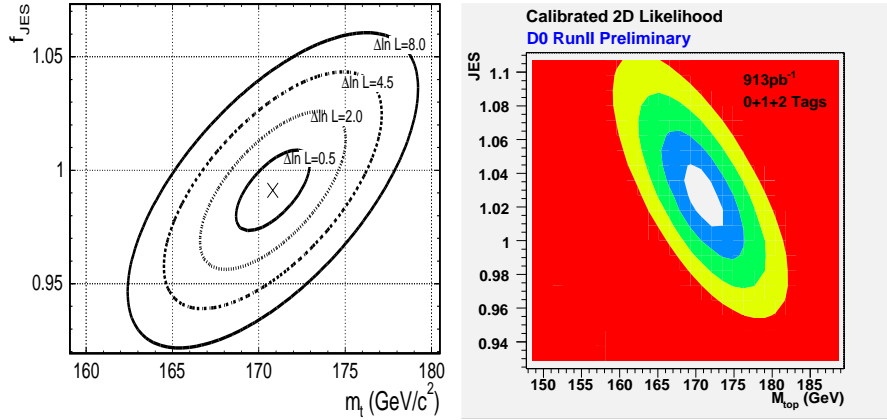
Figure 1: *Likelihood contours obtained using the Matrix Element Method in the lepton-jets channel. Left: CDF result with $955pb^{-1}$; Right: DØ result with $913pb^{-1}$ (shown for e+jets events only).*

The event selection of both experiments usually requires one well contained electron or muon candidate with transverse momentum $p_T > 20\,\text{GeV}/c$, a sizable amount of missing transverse energy $\not{E}_T > 20\,\text{GeV}$ to account for the neutrino, and at least four jets with $E_T \geq 15(20)\,\text{GeV}$ at CDF (DØ). Matrix element measurements are restricted to events with exactly four jets, in order to match the predicted final state partons, whereas template based analyses also allow events with sub-leading jets to pass the selection. Various analyses subdivide the data into disjoint samples with different b-tag cuts in order to handle statistical power against sample purity. The background of this channel mainly consists of W+jets final states (*e.g.* $Wb\bar{b}q\bar{q}$, $Wq\bar{q}q\bar{q}$ with fake b-tags, *etc.*) and QCD multi-jets events in which jets are misidentified as leptons.

Both experiments obtain the most precise results using the Matrix Element Method with *in situ* JES calibration. CDF has analyzed [5] a data sample of $955\,\text{pb}^{-1}$ and found 167 b-tagged candidate events (22 ± 8 expected background). The signal ($\mathcal{P}_{t\bar{t}}$) and background probability densities ($\mathcal{P}_{W+\text{jets}}$) are calculated similarly to Eq. (1) using a $t\bar{t}$ leading order matrix element and a MC based parametrization for the W+jets process (which is also found to adequately describe the QCD multi-jets probabilities). A sample likelihood

$$\mathcal{L}(M_t, \text{JES}) \propto \prod_i^{\#\text{events}} [f_t \mathcal{P}_{t\bar{t}}^{(i)}(M_t, \text{JES}) + (1 - f_t)\mathcal{P}_{W+\text{jets}}^{(i)}(\text{JES})] \qquad (2)$$

is used to extract simultaneously M_t and the JES. The signal fraction f_t is allowed to float. Fig. 1 (left) shows the resulting likelihood contours. The analysis yields $M_t = 170.8 \pm 2.2^{(\text{stat.+JES})} \pm 1.4^{(\text{syst.})}\,\text{GeV}/c^2 = 170.8 \pm 2.6\,\text{GeV}/c^2$, where

the statistical component (stat.+JES) includes an uncertainty of $1.5\,\mathrm{GeV}/c^2$ due to the JES. With a relative uncertainty of 1.5%, this result constitutes the most precise measurement to date.

DØ has reported matrix element analyses [6] based on $913\,\mathrm{pb}^{-1}$ and 507 candidate events with ≥ 0 b-tags (373 ± 39 estimated background). Two measurements are performed, one which uses the b-tagger to assign weights to the jet-quark assignments in the event probabilities, and a second one which focuses on event topology only. The b-tagging analysis calculates individual likelihoods similarly to Eq. (2) for three subsamples with 0, 1 and ≥ 2 b-tags, and joins them using individually optimized values for f_t. Fig. 1 (right) shows the corresponding overall likelihood extracted from an electron-jets subsample. Differently from CDF, a JES prior is used, and also the finite resolution of the electron and muon momentum is considered in the transfer functions. The result obtained is $M_t = 170.5 \pm 2.4^{(\mathrm{stat.+JES})} \pm 1.2^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 170.5 \pm 2.7\,\mathrm{GeV}/c^2$ (1.6% precision), where the uncertainty from the JES is $1.6\,\mathrm{GeV}/c^2$. The result of the pure topological analysis is $M_t = 170.5 \pm 2.5(\mathrm{stat.+JES}) \pm 1.4^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 170.5 \pm 2.9\,\mathrm{GeV}/c^2$ (1.7% precision). The b-tagging analysis is the most precise DØ measurement and in excellent agreement with the CDF result.

The *in situ* JES calibration technique was pioneered by CDF and originally used in Template Method analyses, of which the most recent one [7] uses a data set of $680\,\mathrm{pb}^{-1}$. Four exclusive samples with different S/B ratio and sensitivity to M_t are selected according to different b-tag requirements and jet E_T cuts. For each sample, templates for M_t and the JES are formed using the reconstructed top quark mass (corresponding to the quark-jet assignment with the lowest χ^2) and the invariant W di-jet mass, which are then compared to the data using an unbinned likelihood. A cut to the χ^2 in addition to the standard selection ensures that only well reconstructed events are considered. Using 360 selected candidate events (97 ± 23 background from a constrained fit) the result obtained is $M_t = 173.4 \pm 2.5^{(\mathrm{stat.+JES})} \pm 1.3^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 173.4 \pm 2.8\,\mathrm{GeV}/c^2$ (1.6% precision), which is compatible with the matrix element result. The JES contribution to the statistical uncertainty is $1.8\,\mathrm{GeV}/c^2$. The *in situ* calibration reduced the *a priori* JES uncertainty by about 40%.

CDF has recently demonstrated that the Template Method can be improved by combining the kinematic top quark mass solutions of the three best quark-jet combinations [8]. The analysis addresses the problem that the smallest χ^2 corresponds to the correct association in less than 50% of the time. For each event, the three solutions are combined considering their correlations. A analysis of $1030\,\mathrm{pb}^{-1}$ of data containing 645 candidates (≥ 0 b-tags) yields $M_t = 168.9 \pm 2.2^{(\mathrm{stat.})} \pm 4.2^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 168.9 \pm 4.7\,\mathrm{GeV}/c^2$ (2.8% precision), the best result achieved in this channel without *in situ* JES calibration.

The DØ collaboration has employed the "Ideogram Method" (extended by *in situ* JES calibration) for the first time in the lepton-jets channel us-

ing a $425\,\mathrm{pb}^{-1}$ data sample [9] with 230 candidate events (123 ± 15 expected background). Instead of evaluating matrix elements, the analysis uses the outcome of a kinematic fitter, b-tagging information and a multivariate S/B discriminant to extract per-event probability densities similarly to Eq. (2). The signal probability $\mathcal{P}_{t\bar{t}}$ considers all possible jet-quark permutations, which are weighted according to fit quality and compatibility with b-tag information. The shape of the M_t distribution of the correct permutation is given by a relativistic top quark Breit Wigner function convoluted with an experimental Gaussian resolution function, whereas the shape corresponding to the wrong permutation as well for the background probability density $\mathcal{P}_{W+\mathrm{jets}}$ is derived using appropriate MC simulations. The result obtained is $M_t = 173.7 \pm 4.4^{(\mathrm{stat.+JES})}\ {}^{+2.1}_{-2.0}\ ^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2$ (2.8% precision).

CDF has performed further Template Method analyses in the lepton-jets channel which currently lack statistical precision but are important in the long run because they are aiming at establishing measurements with different inherent systematics. Here we mention the "Decay Length Technique" [10], which uses the transverse distance of a jet's secondary vertex from the primary vertex as a template variable. The method is motivated by the expectation that b-hadrons from top quark decays are boosted and thus correlated with M_t. The analysis solely relies on tracking information and has no JES dependence. Using 375 signal candidates with 456 b-tagged jets found in a $695\,\mathrm{pb}^{-1}$ sample with at least three jets per event yields $M_t = 180.7^{+15.5}_{-13.4}\ ^{(\mathrm{stat.})} \pm 8.6^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2$. Despite the low statistical precision, the method has proven its practicability and can make significant contributions at LHC.

5   Measurements in the Di-Lepton Channel

The di-lepton channel provides pure signal samples but suffer from a poor branching ratio of about 5%. Experimentally, the event kinematics is under-constrained due to the presence of two neutrinos and the availability of just one missing E_T observable. Template-based analyses therefore assume values for certain variables (*e.g.* the neutrino η) in order to extract a solution for the top quark mass, and assign weights to the different solutions. Matrix element analyses "naturally" integrate over unconstrained variables.

For the most recent measurements presented here, both CDF and DØ consider only events containing two well identified electrons or muons. Candidate events must have two oppositely charged leptons with typically $E_\mathrm{T} \geq 20(15)\,\mathrm{GeV}$ in case of CDF (DØ) and at least two jets with $E_\mathrm{T} \geq 15(20)\,\mathrm{GeV}$. The required amount of missing transverse energy is typically higher than in the lepton-jets channel, at least $\not{E}_\mathrm{T} \geq 25(35)\,\mathrm{GeV}$. Additional cuts are applied based on the angle between the $\not{E}_\mathrm{T}$ vector and the transverse direction of the leptons and jets, as well as on further topological variables. For ee and $\mu\mu$ events, the $\not{E}_\mathrm{T}$
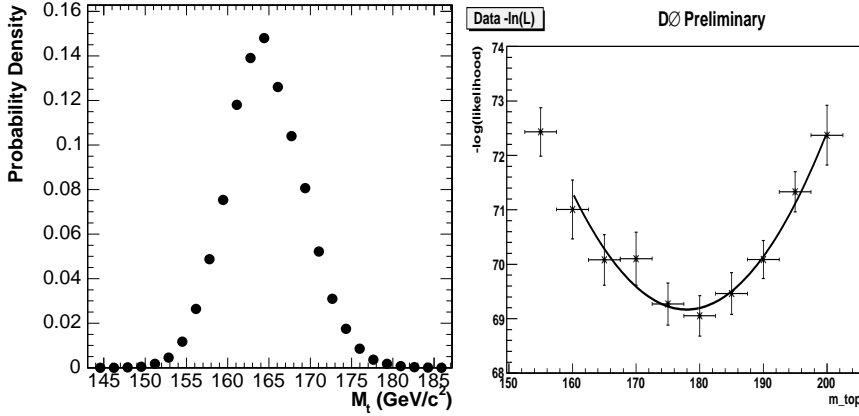
Figure 2: *Di-lepton channel results: Left: Joint likelihood vs. M_t extracted by CDF with the Matrix Element Method ($1030\,pb^{-1}$). Right: Log likelihood curve obtained by DØ using the Matrix Weighting ($835\,pb^{-1}$, $e\mu$ events).*

requirement is modified (or the event is rejected in case of DØ) if the di-lepton invariant mass lies within a given window around the Z boson mass, in order to reduce more effectively background events with $Z \to l^+l^-$ decays. The background is dominated by the Drell-Yan process, di-boson contributions like $WW+2$ jets, and $W+3$ jet events where one jet was misidentified as a lepton. The S/B ratios range from ~2 for ≥ 0 b-tags and ~20 for ≥ 1 b-tag.

The best measurement in this channel is achieved by CDF using the Matrix Element Method [11]. The event probability density is given by a linear combination of the probabilities for the signal and the three major background processes using M_t-dependent weights from MC predictions. The individual probabilities are calculated similarly to Eq. (1), except for the important difference that no JES *in situ* calibration is possible on the basis of the signal process. Additional transfer functions for the $t\bar{t}$ transverse momentum are introduced using the E_T of the sub-leading jets and the unclustered E_T, in order to account for recoil effects induced by ISR. The measurement is calibrated to account for limitations due to background modeling and further simplifying assumptions. From a data set of $1030\,\mathrm{pb}^{-1}$ containing 78 candidate events (27 ± 5 expected background), the likelihood curve shown in Fig. 2 (left) is extracted. The result obtained is $M_t = 164.5 \pm 3.9^{(\mathrm{stat.})} \pm 3.5^{(\mathrm{JES})} \pm 1.7^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 164.4 \pm 5.5\,\mathrm{GeV}/c^2$ (3.3% precision). By including background probabilities, the error is reduced by 15% compared to a measurement based on signal probability only. The analysis was cross-checked using a subset of 30 events with at least one b-tag, yielding $M_t = 167.3 \pm 4.6^{(\mathrm{stat.})} \pm 3.3^{(\mathrm{JES})} \pm 1.9^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 167.3 \pm 6.0\,\mathrm{GeV}/c^2$ (3.6% precision).

The CDF and DØ collaborations have also applied the Template Method in the di-lepton channel. DØ has employed two neutrino solution weighting schemes [12]. The "Neutrino Weighting Method" scans over the top quark mass m_t and the pseudorapidity of the two neutrinos (ignoring the measured $\not{E}_{\mathrm{T}}$), and assigns weights based on the compatibility of the total transverse neutrino energy with the observed $\not{E}_{\mathrm{T}}$. For a given m_t, the weights resulting from all neutrino η assumptions and two possible jet-quark assignments are summed. Detector resolutions are taken into account by averaging the weights from repeated calculations with input observables randomly smeared within their resolutions. M_t templates are formed using the sum of weights versus m_t distributions. The analysis is performed with separate templates for ee, $e\mu$ and $\mu\mu$ events, which are compared with the data using a maximum likelihood fit. Using a sample of $1050\,\mathrm{pb}^{-1}$ containing 57 candidate events ($10.3^{+2.9}_{-3.7}$ expected background), the result obtained is $M_t = 172.5 \pm 5.8^{(\mathrm{stat.})} \pm 5.5^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 172.5 \pm 8.0\,\mathrm{GeV}/c^2$, which is the best single DØ measurement in this channel (4.6% precision).

Another scheme called "Matrix Weighting Method" assumes a value for m_t and calculates the (at most) four corresponding neutrino solutions given the W mass, the jet and charge lepton momenta and $\not{E}_{\mathrm{T}}$. A weight is assigned based on the agreement of matrix element predictions for the charged lepton p_{T} with the observed one. Templates are built using the m_t values giving the maximum event weight, and compared with the data using a binned maximum likelihood fit. Fig. 2 (right) shows the log likelihood curve thus obtained. Using 28 signal candidates in the $e\mu$-channel ($4.4^{+2.6}_{-1.4}$ expected background) selected in a sample of $835\,\mathrm{pb}^{-1}$, DØ extracts $M_t = 177.7 \pm 8.8^{(\mathrm{stat.})}\,^{+3.7}_{-4.5}\,^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 177.7 \pm 9.7\,\mathrm{GeV}/c^2$ (5.5% precision).

CDF has also used the Neutrino Weighting Method in early Run-II as well as a weighting scheme which scans the neutrino's azimuth angle. Here we report on a more recent measurement known as "Full Kinematic Method" [13]. The analysis assumes that the distribution of the longitudinal momentum $p_z(t\bar{t})$ of the $t\bar{t}$ system is a zero-centered Gaussian with $195\,\mathrm{GeV}/c$ width, as indicated by MC simulations and supported by lepton-jets data. Studies show that the $p_z(t\bar{t})$ distribution has no mass dependence and is equal for $t\bar{t}$ and background. Given $p_z(t\bar{t})$ and using the known b and W masses, one can solve the kinematic equations numerically. The finite resolution is taken into account by smearing the b-quark energies, $\not{E}_{\mathrm{T}}$ and $p_z(t\bar{t})$ within the expected uncertainties, and repeatedly solving the equations. From the resulting m_t distribution, the most probable value is taken to build templates separately for events with and without b-tag. A maximum likelihood fit to a $1.2\,\mathrm{fb}^{-1}$ data set with 70 candidates (26 ± 6 background) yields $M_t = 169.1^{+5.2}_{-4.9}\,^{(\mathrm{stat.})} \pm 2.9^{(\mathrm{JES})} \pm 1.0^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 169.1 \pm 5.9\,\mathrm{GeV}/c^2$ (3.5% precision). This is the most precise template-based measurement in the di-lepton channel to date.

6 Measurements in the All-Jets Channel

Measurements in the all-jets channel are motivated by the high branching ratio of 44% and the complete reconstruction of the top quarks, relying only on hadronic jets. The final state has well-defined kinematics because no neutrino appears. The channel is challenging due to the huge background contamination and the large combinatorial jet-quark ambiguity. Making no flavor requirement and treating top-antitop permutations and the W di-jet permutations equally gives 90 combinations.

So far, only the CDF collaboration has reported measurements in this channel. The expected multi-jets final state has spherical topology and well-balanced visible energy. The selection therefore requires exactly six well-contained jets with $E_T > 15\,\mathrm{GeV}$ and a missing E_T significance $\not{E}_T/\sqrt{\sum E_T} < 3\,\mathrm{GeV}^{\frac{1}{2}}$. Events containing high p_T electrons or muons are rejected. Further cuts on kinematic and topological variables are applied to purify the sample. The remaining background is dominated by QCD multi-jet events ($bb4q$, $6q$).

The first published Run-II measurement in the all-jets channel is based on the Ideogram Method [14]. The selection used in this analysis yields S/B∼1/25 without b-tagging (compared to ∼1/3500 at trigger level) and S/B∼1/5 including b-tag information. Similar to the DØ lepton-jets ideogram analysis described in Sec.4, individual signal probability densities for the right and wrong jet-quark permutations as well as background probability densities are formed, and weights are assigned using the fit χ^2 and a b-tag probability measure. To improve the S/B discrimination in the kinematic fit, the probabilities are expanded in two dimensions using the invariant masses of both the top and the antitop quark. For the signal they are indistinguishable and expected to peak at the "right" value for M_t, but for background events at least one peaks at too low values. The sample likelihood allows for a simultaneous optimization of both M_t and the sample purity, because the QCD background cross sections are not well known. The result obtained using 290 b-tagged signal candidates in a $310\,\mathrm{pb}^{-1}$ sample is $M_t = 177.1 \pm 4.9^{(\mathrm{stat.})} \pm 4.3^{(\mathrm{JES})} \pm 1.9^{(\mathrm{syst.})}\,\mathrm{GeV}/c^2 = 177.1 \pm 6.8\,\mathrm{GeV}/c^2$ (3.8% precision).

The precision in the all-jets channel is greatly improved in a recent template analysis [15] due to the adoption of the JES *in situ* technique and pushing the S/B ratio to ∼1. The latter was achieved using a novel neural network approach and by considering samples with one and ≥ 2 b-tags separately. The signal templates are obtained using matrix element calculations and transfer functions, the background probabilities are given by a data driven model using the 0 b-tag sample, which has negligible signal fraction. Priors for the JES and the number of observed and background events are used. Fig. 3 (left) shows the likelihood contours extracted from $943\,\mathrm{pb}^{-1}$ data containing 72 signal candidates (∼44 estimated background). The good S/B ratio achieved in this
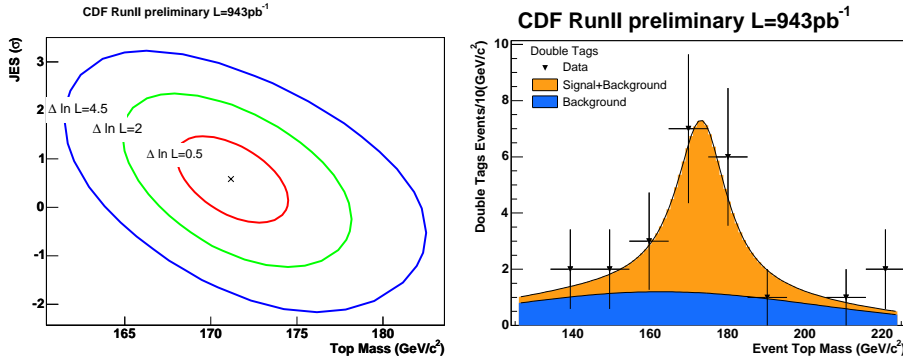
Figure 3: *Left: Likelihood contours extracted by CDF from 943 pb^{-1} data using the Template Method with JES in situ calibration. Right: Top quark mass distribution in data and simulation for doubly tagged events.*

channel is illustrated in Fig. 3 (right), which shows the doubly b-tagged sample together with the fitted signal and background templates. The analysis yields $M_t = 171.1 \pm 2.8^{\text{(stat.)}} \pm 2.4^{\text{(JES)}} \pm 2.1^{\text{(syst.)}} \text{ GeV}/c^2 = 171.1 \pm 4.3 \text{ GeV}/c^2$ (2.5% precision). The JES uncertainty is much reduced compared to a traditional one-dimensional template analysis [16] based on $1020\,\text{pb}^{-1}$ data containing 772 b-tagged candidate events, which yields $M_t = 174.0 \pm 2.2^{\text{(stat.)}} \pm 4.5^{\text{(JES)}} \pm 1.7^{\text{(syst.)}} \text{ GeV}/c^2 = 174.0 \pm 5.3 \text{ GeV}/c^2$ (3.0% precision).

7 Systematic Uncertainties

So far, the systematic uncertainties of M_t in all channels are dominated by contributions from the JES. The di-lepton channel has the biggest JES uncertainty because no *in situ* calibration is performed here. Other significant sources are primarily related to the MC simulation. For the best results presented in this report, these are the modeling of gluon ISR and FSR (particularly in the all-jets and lepton-jets channel), the proton-parton density function, the hadronization model, and the modeling of the background (specially in the all-jets channel). The individual contributions are $\sim 1 \text{ GeV}/c^2$ or less, and are expected be the limiting factor in the precision of M_t at the end of Run-II.

8 Tevatron Combination

CDF and DØ have updated the combination of their best results achieved in each channel [17] (see Fig. 4, left), which includes the most precise measurements reported in Sec. 4, 5 and 6. Also the result from the Decay Length Tech-
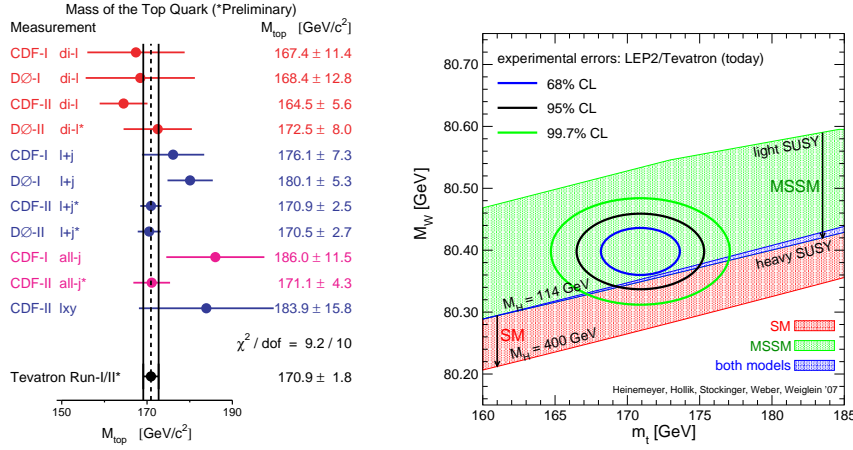
Mass of the Top Quark (*Preliminary)

Measurement M_{top} [GeV/c^2]

Measurement		M_{top} [GeV/c^2]
CDF-I	di-l	167.4 ± 11.4
DØ-I	di-l	168.4 ± 12.8
CDF-II	di-l	164.5 ± 5.6
DØ-II	di-l*	172.5 ± 8.0
CDF-I	l+j	176.1 ± 7.3
DØ-I	l+j	180.1 ± 5.3
CDF-II	l+j*	170.9 ± 2.5
DØ-II	l+j*	170.5 ± 2.7
CDF-I	all-j	186.0 ± 11.5
CDF-II	all-j*	171.1 ± 4.3
CDF-II	lxy	183.9 ± 15.8

χ^2 / dof = 9.2 / 10

Tevatron Run-I/II*   170.9 ± 1.8

M_{top} [GeV/c^2]

experimental errors: LEP2/Tevatron (today)
— 68% CL
— 95% CL
— 99.7% CL
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM / MSSM / both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '07
M_W [GeV]
m_t [GeV]

Figure 4: *Left: M_t measurements used to calculate the current world average. Right: M_t versus M_W in the SM and the MSSM compared with the present measurements shown as confidence level contours* [19].

nique is considered since its experimental systematics are largely uncorrelated with those of other methods. Taking all correlations between the systematic uncertainties properly into account, the new world average value obtained is $M_t = 170.9 \pm 1.1^{(\text{stat.})} \pm 1.5^{(\text{syst.})} \,\text{GeV}/c^2 = 170.9 \pm 1.8 \,\text{GeV}/c^2$. The χ^2/d.o.f. of 9.2/10 (51% probability) indicates a good agreement among all measurements. New M_t averages are also calculated individually for each channel: $172.2 \pm 4.1 \,\text{GeV}/c^2$ (all-jets), $171.2 \pm 1.9 \,\text{GeV}/c^2$ (lepton-jets), $163.2 \pm 4.5 \,\text{GeV}/c^2$ (di-lepton). The results are consistent given their correlations.

9   Conclusions

The CDF and DØ collaborations have established a robust top quark mass measurement program based on a variety of techniques applied to different $t\bar{t}$ final states. The previous Run-I errors have been reduced by a factor of 2-3 in each decay channel. An important achievement is the reduction of the JES uncertainty due to *in situ* calibration, which is a reason why the all-jets channel has become competitive. The new world average value for the top quark mass is $M_t = 170.9 \pm 1.8 \,\text{GeV}/c^2$, which corresponds to a precision of 1.1%. The effect of M_t and the recently updated M_W measurement [18] on the mass of the Higgs boson is shown in Fig. 4 (right). The uncertainties translate to a $\sim$30% constraint for M_H. With full Run-II data, the uncertainty in M_t may be even pushed to $1 \,\text{GeV}/c^2$, which is also expected after 5-10 years of LHC operation. The top quark mass might thus be the lasting legacy of the Tevatron.

Acknowledgments

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